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Searches for Beyond the MSSM Phenomena at CDF

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Abstract. CDF searches for R_p violation, extra quark generations, and long-lived charged massive particles are presented. These phenomena are not predicted by the Minimal Supersymmetric Standard Model (MSSM) and therefore complement the classic SUSY searches. Prospects for continuing these analyses during Run II of the Tevatron are outlined.

INTRODUCTION

The minimal supersymmetric standard model (MSSM) [1] is an extension of the standard model (SM) that adds a supersymmetric (SUSY) partner for each SM particle, and is constructed to conserve R parity (R_p): for a particle of spin S , the multiplicative quantum number $R_p \equiv (-1)^{3B+L+2S}$ distinguishes particles ($R_p = +1$) from SUSY particles ($R_p = -1$). Here B and L are baryon and lepton number, respectively. The assumption of R_p conservation leads to experimental signatures with appreciable missing transverse energy (\cancel{E}_T), provided that the lightest supersymmetric particle (LSP) is electrically neutral and colorless. In general, however, the superpartners of quarks and leptons can undergo R_p violating (\cancel{R}_p) interactions and such models can be built by adding explicitly B or L violating terms to the SUSY Lagrangian. These additional \cancel{R}_p couplings allow for the decay of the LSP and reduce the \cancel{E}_T signature seen in the MSSM. If the LSP is charged and has an appreciable lifetime (or is stable), it can be detected in a search for charged massive particles (CHAMPs). Finally, while the MSSM makes no predictions regarding the possibility of extra quark families, there is no theoretical reason against them [2].

CDF has performed searches for these phenomena using data taken with the Run I detector [3]. Upgrades of both the detector and Tevatron are currently underway [4]. These will provide substantial enhancements for these and other searches in Run II, scheduled to begin in 2000. During this run, CDF II will collect roughly 2 fb^{-1} of data at $\sqrt{s} = 2 \text{ TeV}$, corresponding to twenty times the present statistics. The 10% increase in energy corresponds to a 40% increase in the $t\bar{t}$ yield, and similarly will aid new phenomena searches.

R_p VIOLATION SEARCH USING LIKE-SIGN DIELECTRONS

Events with a positron and a jet at high Q^2 values, detected at the HERA experiments [5], have sparked interest in R_p violating SUSY, since such events can be explained by the production and decay of a charm squark (\tilde{c}_L): $e^+ + d \rightarrow \tilde{c}_L \rightarrow e^+ + d$, where R_p is violated at both vertices. For this scenario, \tilde{c}_L with mass $M(\tilde{c}_L) \simeq 200 \text{ GeV}/c^2$ is the preferred squark flavor, because its associated coupling λ'_{121} [6,7] is less constrained by experiment than the others.

Two \cancel{R}_p processes that involve the same λ'_{121} coupling are tested [8]: (i) $p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow (c\tilde{c}_L)(c\tilde{c}_L) \Rightarrow c(e^\pm d)c(e^\pm d)$ “charm squark analysis”; and (ii) $p\bar{p} \rightarrow \tilde{q}\tilde{q} \rightarrow (q\tilde{\chi}_1^0)(\bar{q}\tilde{\chi}_1^0) \Rightarrow q(dce^\pm)\bar{q}(dce^\pm)$ “neutralino analysis”. Here, the \cancel{R}_p decays are indicated by “ \Rightarrow .” For process (i) we assume $M(\tilde{g}) > M(\tilde{c}_L) = 200 \text{ GeV}/c^2$. The masses of the other squarks are given in a MSSM scenario in Ref. [6]. For process (ii), we consider $\tilde{q}\tilde{q}$ production (5 degenerate squark flavors) and $\tilde{t}_1\tilde{t}_1$ production separately. We also make the mass assumptions: $M(\tilde{\chi}_1^\pm) > M(\tilde{q}) > M(\tilde{\chi}_1^0)$, $M(\tilde{\chi}_1^\pm) \approx 2M(\tilde{\chi}_1^0)$, and $M(\tilde{\chi}_1^\pm) > M(\tilde{t}_1) - M(b)$, where the first relation suppresses $\tilde{q} \rightarrow \tilde{\chi}_1^\pm$, the second relation arises from gaugino mass unification, and the third ensures that $Br(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$ for $M(\tilde{t}_1) < M(t)$. Given the Majorana nature of the gluino and neutralino, reactions

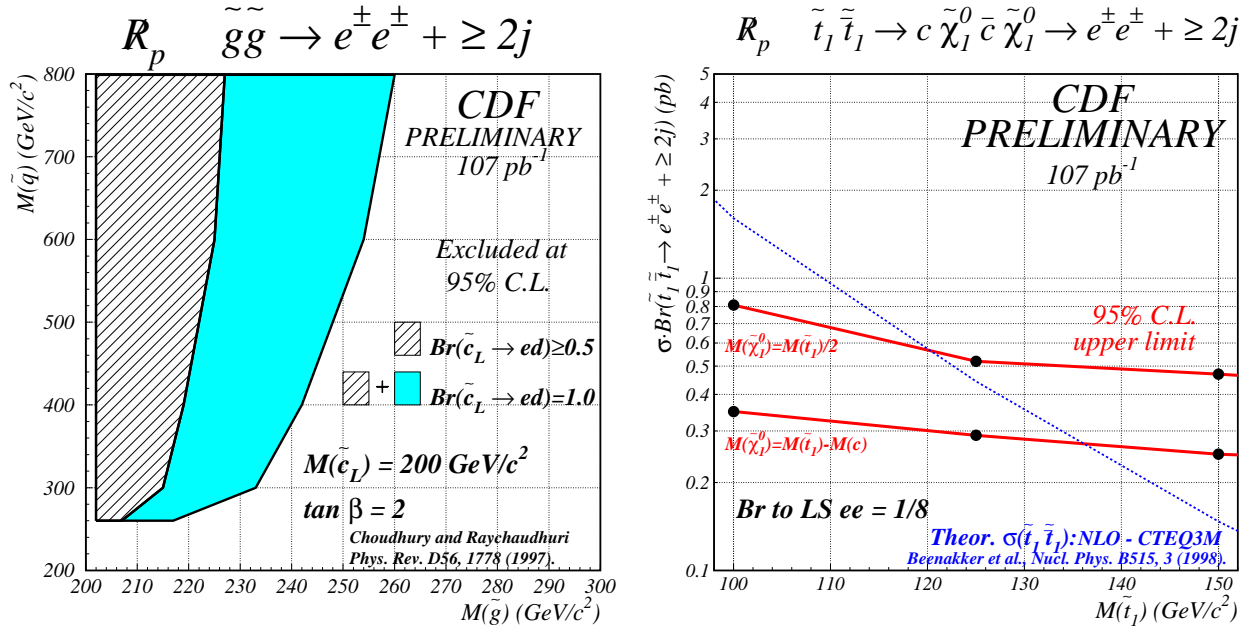


FIGURE 1. Exclusion regions in the $M(\tilde{q})$ - $M(\tilde{g})$ plane (left) and upper limits on cross section times branching ratio for $\tilde{t}_1 \tilde{t}_1$ production (right).

(i) and (ii) yield like-sign (LS) and opposite-sign (OS) dielectrons with equal probability. Since LS dilepton events have the benefit of small SM backgrounds, we search for events with LS electrons plus two or more jets.

This analysis requires at least two electrons with $E_T > 15$ GeV in the central electromagnetic calorimeter. The η - ϕ separation $\Delta R_{ee} \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between two electrons must be greater than 0.4. Each electron must pass an isolation cut which requires the total calorimeter E_T in an η - ϕ cone of radius $\Delta R = 0.4$ around the electron, excluding the electron E_T , to be less than 4 GeV. Jets are identified in the calorimeter using cone size $\Delta R = 0.7$ for clustering and in the range $|\eta_j| < 2.4$. There must be at least two jets with $E_T > 15$ GeV, $\Delta R_{jj} > 0.7$, and $\Delta R_{ej} > 0.7$. We further require no significant \cancel{E}_T in the event: $\cancel{E}_T / \sqrt{\sum E_T} < 5 \text{ GeV}^{1/2}$. No LS ee events survive our selection. The remaining 166 OS ee events are consistent with expected contributions from SM processes, notably Drell-Yan production of dielectrons.

Event acceptances are calculated using Monte Carlo samples generated with ISAJET, CTEQ3L parton distribution functions, and passed through the CDF detector simulation program. SM backgrounds for this search, $t\bar{t}$ and $b\bar{b}/c\bar{c}$ production, are small. We find the total background in 107 pb^{-1} is consistent with zero events. We set limits on the cross section times branching ratio for the two processes under study. For the charm squark analysis, the event acceptance is a very weak function of $M(\tilde{g})$ in the range of 16.0% to 16.6%; we include a 10% systematic uncertainty (dominated by the uncertainty on the integrated luminosity), and exclude $\sigma \cdot Br \geq 0.18 \text{ pb}$ independent of $M(\tilde{g})$. In Figure 1 we plot the results from the charm squark analysis in the gluino-squark mass plane. Contours are shown for two values of the branching ratio $Br(\tilde{c}_L \rightarrow ed)$, where we have compared our results to the NLO $\tilde{g}\tilde{g}$ production cross section multiplied by the branching ratio to LS ee from Ref. [7].

For the neutralino analysis, the acceptance is determined for each squark and neutralino mass pair and ranges from 3.7% to 15.2%. We obtain $\sigma \cdot Br$ limits which range as a function of the squark mass from 0.81 pb to 0.26 pb for a light neutralino, and from 0.35 pb to 0.20 pb for a heavy neutralino. Figure 1 shows the results for the neutralino analysis for the case of $\tilde{t}_1 \tilde{t}_1$ production. Plotted are our 95% C.L. upper limits along with the cross section times branching ratio versus $M(\tilde{t}_1)$ from the NLO prediction. The branching ratio $Br(\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0)$ is taken to be 1.0. We also assume $Br(\tilde{\chi}_1^0 \rightarrow q\bar{q}'e) = Br(\tilde{\chi}_1^0 \rightarrow q\bar{q}'\nu) = 1/2$. Since each neutralino decays to e^+ or e^- with equal probability, the branching ratio to LS ee is $1/8$. This analysis excludes $M(\tilde{t}_1)$ below 120 (135) GeV/c² for a light (heavy) neutralino. The results for the neutralino analysis for the case of five degenerate $\tilde{q}\tilde{q}$ production are displayed in Figure 2. Again, plotted is our cross section times branching ratio limit for two neutralino masses, along with the NLO prediction which includes a gluino mass dependent t -channel contribution to the cross section. Thus, we set gluino and neutralino mass-dependent lower limits on

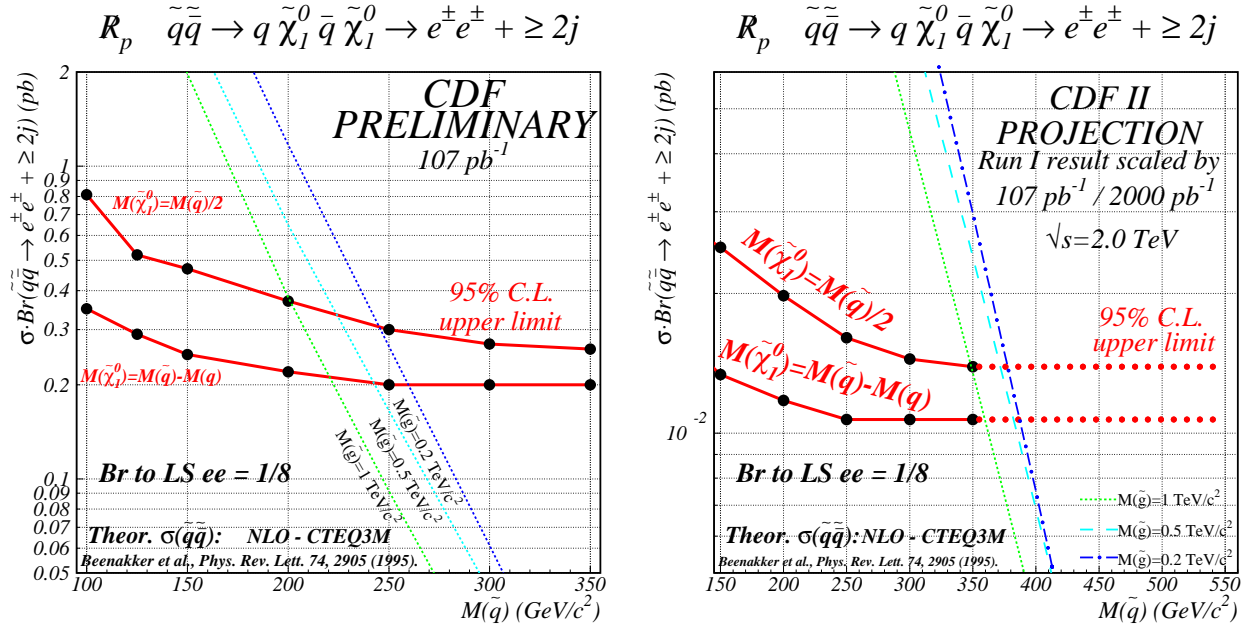


FIGURE 2. Upper limits on cross section times branching ratio for five-flavor degenerate $\tilde{q}\tilde{q}$ production (left) and projection for Run II (right). Also shown are the NLO cross sections multiplied by a branching ratio to LS ee of $1/8$ with the assumption of $Br(\tilde{q} \rightarrow q\tilde{\chi}_1^0) = 1.0$.

the degenerate squark mass in the range from 200 to 260 GeV/c^2 .

We include a Run II projection for this search in Figure 2 which folds in the increased cross section at $\sqrt{s} = 2 \text{ TeV}$ along with the ratio of the integrated luminosities. Assuming event selection and background levels similar to those in Run I, this search will be sensitive to squark masses up to 380 GeV/c^2 . The addition of the muon channel will further enhance the reach, as will the improved lepton identification in Run II.

R_p VIOLATION SEARCH USING MULTILEPTON EVENTS

If, instead of the assumption in the previous analysis, one of the λ couplings is non-zero, events with extra leptons can be expected. CDF has an analysis underway that examines $\lambda_{121} \neq 0$ [9]. This relation leads to two classes of processes: 1) direct decays of sleptons and sneutrinos to leptons and neutrinos, and 2), decays of charginos and neutralinos to leptons and neutrinos. It is further assumed that λ_{121} is large enough so that the R_p decays are prompt (i.e., within $\mathcal{O}(1\text{mm})$ of the interaction point, but also that $\lambda_{121} \ll 1$. This tends to suppress both 1) and 2), except for decays of the LSP which have no competing MSSM decays. Thus, $\tilde{\chi}_1^0 \rightarrow \mu\bar{\nu}_e, \bar{\mu}\bar{\nu}_e, e\bar{\nu}_\mu, e\bar{e}\bar{\nu}_\mu$ each with equal probability. Such events therefore contain four (or more) leptons and \cancel{E}_T .

Simulation of the signal is performed using ISAJET within a SUGRA framework. The mass parameters M_0 and $M_{1/2}$ are input, while the others are fixed: $A_0 = 0$, $\tan\beta = 2$, $\text{sgn}\mu = -1$. The event selection requires four leptons, $\ell = (e, \mu)$, where one lepton satisfies $E_T(e) > 12 \text{ GeV}$, $|\eta_e| < 1.1$ or $p_T(\mu) > 12 \text{ GeV}/c$, $|\eta_\mu| < 0.6$, while the others must satisfy $E_T(e) > 5 \text{ GeV}$, $|\eta_e| < 1.1$ or $p_T(\mu) > 5 \text{ GeV}/c$, $|\eta_\mu| < 1.0$. Furthermore, the leptons must be separated by $\Delta R > 0.4$. Neither lepton isolation nor \cancel{E}_T requirements are imposed. SM processes that can yield four lepton events include $t\bar{t}$, $b\bar{b}/c\bar{c}$, and $Z^0 Z^0$ production and decay, although the rates are very low. Another background under study is that of processes containing three real leptons plus an additional fake lepton.

Projections for this search in Run II are presented in Table 1, which folds in the approximate factor of twenty in statistics and the increase in \sqrt{s} . The background increase to $\mathcal{O}(10)$ events in Run II could be controlled by additional cuts on \cancel{E}_T , jets, or lepton isolation. Improvements to the detector, for example the upgraded plug EM calorimeter, will improve the lepton identification efficiency. Such contributions are not included in this estimate.

TABLE 1. Multilepton \mathcal{R}_p search projections for Run II. The efficiencies are based on the Run I detector simulation.

M_0 (GeV/ c^2)	$M_{1/2}$ (GeV/ c^2)	σ (pb)	Efficiency	Four-Lepton Events
50	190	0.170	0.19	64
100	190	0.170	0.12	41
150	190	0.166	0.10	34
200	190	0.166	0.09	31
200	200	0.128	0.10	25
200	210	0.102	0.10	21
200	220	0.078	0.10	16
200	230	0.061	0.10	12
200	240	0.049	0.10	10

SEARCHES FOR A FOURTH GENERATION QUARK

Although the LEP data at the Z^0 pole exclude extra fermion generations with light neutrinos [10], models including fourth family quarks have received recent theoretical attention [2,11]. CDF performs three complementary searches for such quarks, described below.

Search for long-lived parent of the Z^0

CDF performs a general search for long-lived particles decaying to Z^0 bosons [12]. One example is a b' quark decaying via a FCNC to a b quark and a Z^0 . This decay can dominate (depending on the b' mass) but may lead to a long lifetime. Another example is low-energy symmetry breaking models with SUSY [13] that predict the decay $\tilde{\chi}_1^0 \rightarrow Z^0 \tilde{G}$ with a long lifetime due to the small coupling constant of the gravitino.

The technique for this search is to select e^+e^- pairs from Z^0 decay and search the transverse decay length distribution for evidence of Z^0 bosons originating at a displaced vertex. Electrons (e^+ or e^-) are required to satisfy $E_T > 20$ GeV, $p_T > 15$ GeV/ c , and $|\eta| < 1$, with the pair reconstructing to the Z^0 mass: $|M_{ee} - M_{Z^0}| < 15$ GeV/ c^2 . Quality cuts are imposed to reduce the effects of misreconstructed tracks. The e^+ and e^- are required to originate from a common vertex, and nearly collinear tracks are removed by requiring $|\Delta\phi - \pi| > 0.02$. A high-purity sample of $J/\psi \rightarrow \mu^+\mu^-$ is used to check that these cuts do not introduce lifetime biases. In 90 pb $^{-1}$, 703 events pass the full selection.

The reconstructed transverse decay length L_{xy} distribution from these events is clustered around the origin, as expected, and can be modeled with a central gaussian and tails due to tracking errors. The negative L_{xy} region is used to estimate the background from tracking errors and select an L_{xy} cut which is then used to search for a signal in the positive L_{xy} region. A cut of $L_{xy} > 1mm$ is chosen, which corresponds to an expectation of \leq one event based on the central gaussian. There is one candidate event with $L_{xy} > +1mm$. As the data are consistent with background levels, limits are derived as shown in Figure 3. The left figure shows the model independent cross section times branching ratio limit as a function of the lifetime, as well as a limit (insert) for the case of $b' \rightarrow bZ^0$. In this case two jets with $E_T > 10$ GeV and $|\eta| < 2$ are additionally required and the L_{xy} cut is made at 0.1mm. Also shown (right) is the resulting limit on the b' mass as a function of the lifetime.

Plans for the continuation of this analysis in Run II include the addition of the muon channel and an attempt to perform the search using only the outer tracking chamber without the SVX. The former would increase the cross section sensitivity by approximately a factor of two while the latter would flatten out the limit to ~ 30 cm. Folding in the other factors for Run II improvements and integrated luminosity, the present cross section limit minimum of 0.5 pb for the model independent case should be reduced to below 5 fb. For the b' model, masses up to the top quark mass should be excluded in Run II.

Search for $b'\bar{b}' \rightarrow Z^0 Z^0 b\bar{b} \rightarrow (\ell^+ \ell^-)(q\bar{q})(b\bar{b})$

If a fourth generation b' quark is lighter than both t and t' , then the allowed CC decay $b' \rightarrow cW^-$ is doubly Cabbibo suppressed and the FCNC decay $b' \rightarrow bZ^0$ dominates if $m_{b'} > m_{Z^0} + m_b$. At the Tevatron, b'

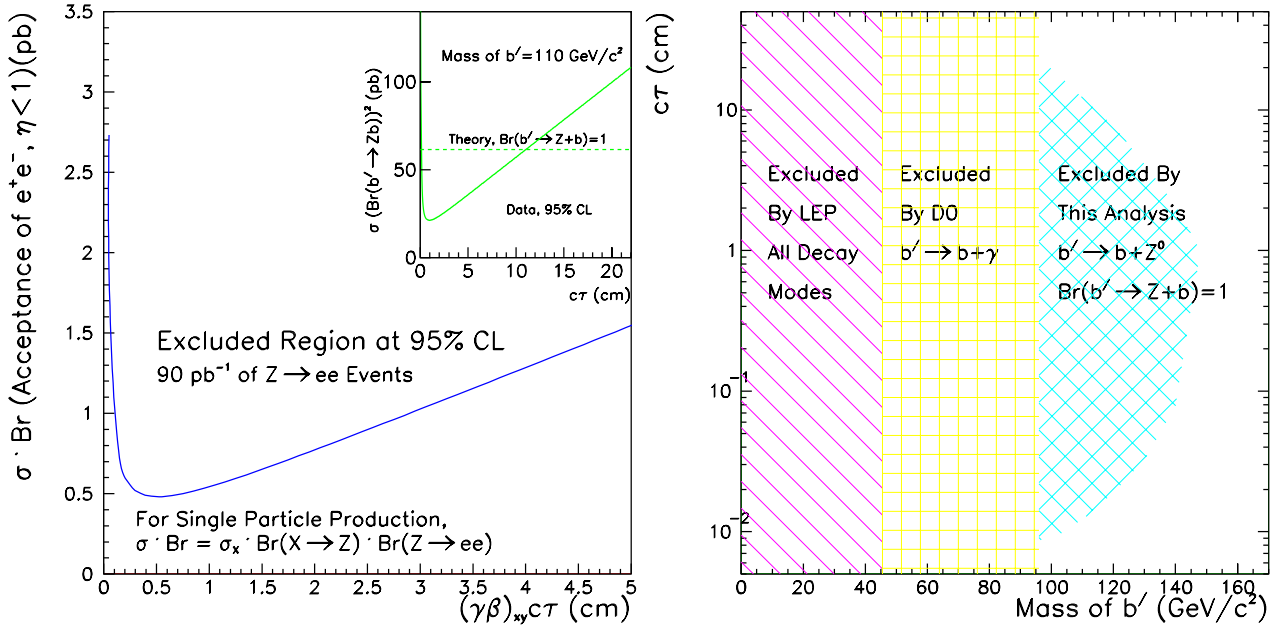


FIGURE 3. Search for a long-lived parent of the Z^0 . Cross section limit (left) and mass limit (right).

would be pair produced with a cross section like that for top with $b'\bar{b}' \rightarrow Z^0 Z^0 b\bar{b} \rightarrow (\ell^+ \ell^-)(q\bar{q})(b\bar{b})$ as one decay pattern. CDF performs a search for such a b' by requiring two electrons consistent with $Z^0 \rightarrow e^+ e^-$, with $E_T(e_1) > 20$ GeV, $E_T(e_2) > 10$ GeV, and $75 \text{ GeV}/c^2 \leq M(e^+ e^-) \leq 105 \text{ GeV}/c^2$. In 87 pb^{-1} , 6548 events satisfy this electron selection. Three or more jets with $|\eta| < 2$ are then required. For the search region $M(b') < 130 \text{ GeV}/c^2$, two jets must satisfy $E_T > 15$ GeV while the third can have $E_T > 7$ GeV. For $M(b') > 130 \text{ GeV}/c^2$, all jets must satisfy $E_T > 15$ GeV. Also, the sum of the jet E_T for jets with $E_T > 15$ GeV must scale with the b' mass in the following way: $\sum E_T(E_T(j) > 15 \text{ GeV}) > M(b') - 60 \text{ GeV}$, motivated by a study of the backgrounds. Finally, one b tag (displaced vertex) using the SVX detector information is required for the event to pass. This final requirement removes the 31 events remaining after the sum E_T requirement.

The b' signal is generated using HERWIG, with masses in the range $100 \text{ GeV}/c^2 \leq M(b') \leq 170 \text{ GeV}/c^2$ and passed through the CDF detector simulation program. The efficiency for $Z^0 \rightarrow e^+ e^-$ is about 60% and the efficiency for the 3 jet cut ranges from 25% to 66% with $M(b')$. The main background process for $b' \rightarrow bZ^0$ comes from $Z^0 + n \text{ } j$ events, where $n \geq 3$, and are modeled using VECBOS and HERWIG. These events are passed through the CDF detector simulation program and filtered with the same event selection as for the signal.

Presently, this analysis is being finalized and the muon channel is being added. Including this additional acceptance along with the improvements expected in Run II described above, the ultimate sensitivity of the search will reach $M(b') \simeq M(t)$. It should be noted that the decay $b' \rightarrow bH$ must be considered in this regime. However, if $H \rightarrow b\bar{b}$ is appreciable, much of the signal can be recovered as long as $b' \rightarrow bZ^0$ remains large enough to provide triggerable leptons from $Z^0 \rightarrow \ell^+ \ell^-$.

Search for long-lived charged massive particles

Several models outside the MSSM predict new charged massive particles (CHAMPs) with appreciable lifetimes. These include fourth generation leptons and quarks, weak R_p violation, and gauge mediated SUSY

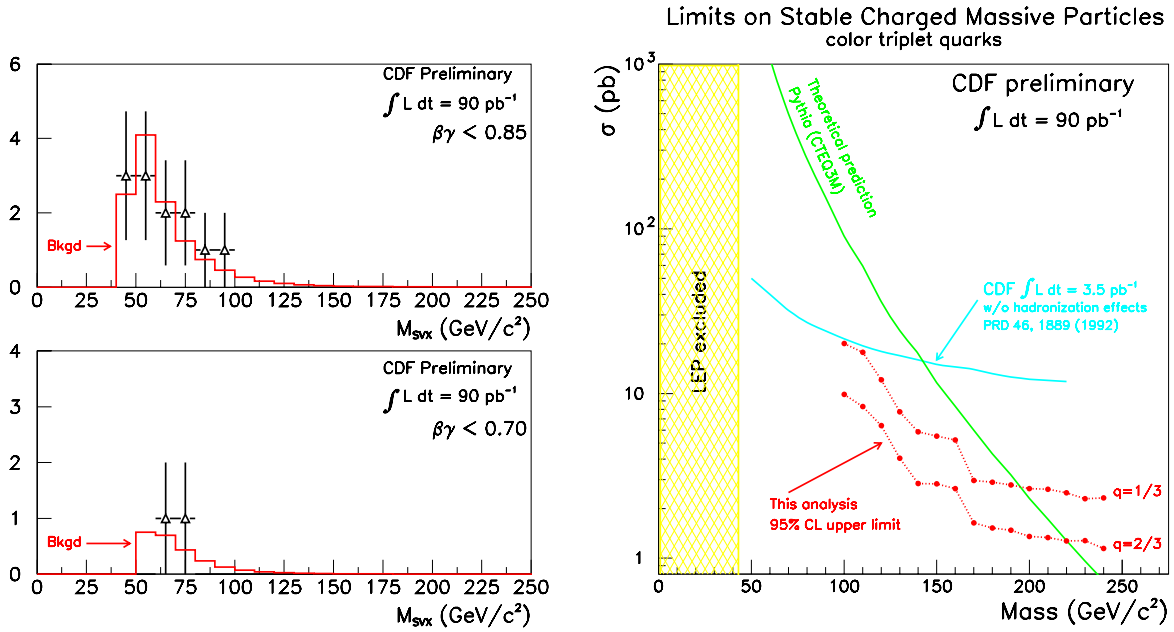


FIGURE 4. Search for strongly interacting CHAMPs. Masses reconstructed using the SVX for two values of the cut on $\beta\gamma$ (left) and mass limit (right).

breaking models. A strongly interacting CHAMP would have a large cross section (like that for top), which allows large masses to be probed with little background. CDF performs such a search using as a reference model a fourth generation quark with fragmentation to an integer charged meson within a jet.

The technique for this search is to use the large ionization energy loss, dE/dx , in the tracking chambers to tag massive (and therefore slow-moving) particles. Starting with 90 pb^{-1} of data from Run I, various tracking cuts for the SVX and central tracker (CTC) are applied to select high quality tracks. Candidate tracks are required to have $|p| > 35 \text{ GeV}/c$ and $|\eta| < 1$ and to pass ionization cuts in both the SVX and CTC which correspond to requiring $\beta\gamma < 0.85$. Finally, a mass is calculated from the momentum and dE/dx and a sliding cut, $M_{dE/dx} > 0.6 M_{CHAMP}$, is applied for each assumed M_{CHAMP} .

The background to this search is due to particles which fake a large ionization signal, mostly from particles whose tracks overlap. The probability of a track faking a signal in both the SVX and CTC is quite low: of the 20K events passing the selection cuts, 12.1 ± 1.8 tracks from fakes are expected with $\beta\gamma < 0.85$. Since the background is higher at low mass, a tighter cut of $\beta\gamma < 0.7$ is used for the search region $M_{CHAMP} < 100 \text{ GeV}/c^2$. With this cut, 2.5 ± 0.8 tracks from fakes are expected. These background levels agree well with the data as shown in Figure 4. The overall efficiency for this search ranges from 0.75% to 3% as a function of the mass of the CHAMP and is about twice as high for assumed charge $+2/3$ as for charge $-1/3$ due to fragmentation effects. Systematic uncertainties for this analysis are dominated by the uncertainty on interactions of a massive quark in the calorimeter which contribute between 13 and 20% depending upon the assumed quark charge. Figure 4 also shows the resulting cross section limits for this analysis. Comparing these curves to the cross section prediction from PYTHIA, mass limits are obtained at $190 \text{ GeV}/c^2$ for b' and $220 \text{ GeV}/c^2$ for t' .

In Run II, the CHAMP search will be enhanced by the larger integrated luminosity, higher cross section ($\sim 40\%$), and improved detector acceptance ($\sim 80\%$) due to the new tracking chambers. Moreover, there is a proposal to include a time of flight system to the CDF detector. This will greatly help searches for weakly interacting CHAMPs, and will improve the acceptance for analysis described here by $\sim 50\%$. Combining these factors, the Run II cross section limit for strongly interacting CHAMPs should reduce to 20 fb.

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